2012 ANNUAL REPORT FOR ONR SPONSORED RESEARCH:

Continued Analysis on Multiscale Aspects of Tropical Cyclone Formation, Structure Change and Predictability in the Western North Pacific Region as Part of the TCS08 DRI

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LONG-TERM GOALS AND OBJECTIVES

The overarching objectives of this research project are to obtain an improved understanding of the formation, intensification, predictability and structure change of tropical cyclones in the Western Pacific region. These new insights will ultimately improve forecast guidance for U.S. Naval operations in this region.

APPROACH

During this past year the PI and his research group have developed and further substantiated a new model for the phenomenon of secondary eyewall formation (**SEF**), a process that occurs frequently in mature tropical cyclones and is a continued forecast priority for storms threatening Naval and DOD operations in the Western North Pacific sector. The new model is based on a newly articulated paradigm of tropical cyclone intensification (discussed further below) that the PI has developed in collaboration with his distinguished international colleague, Professor Roger Smith from the University of Munich. Because of space constraints, only pertinent background information is provided to explain the basis for the new approach followed by a summary of some of the key new findings on the SEF problem. Other research supported by this grant is discussed in preceding annual reports and via the PI's website listed above.

Recent developments in tropical cyclone intensification theory

A new paradigm of tropical cyclone intensification and hurricane boundary layer dynamics has been developed by the PI and his distinguished scientific colleague, Professor Roger Smith. The intensification paradigm begins with the recognition of the inherent three-dimensional nature of the intensification process and emphasizes the aggregate effects of the rotating deep convective structures that drive the spin-up process (Nguyen et al. 2008, Montgomery et al. 2009, Smith et al. 2009, Bui et al. 2009, Montgomery et al. 2010, and Fan and Zhang 2010). From the standpoint of the mean-field dynamics, which is associated with azimuthally averaging the three-dimensional state variables around the system circulation center, the rotating deep convective structures have been implicated in two mechanisms for spinning up the mean vortex:

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1. The first mechanism is associated with the radial convergence of absolute angular momentum (M) and its material conservation[1] above the boundary layer. This mechanism produces convergence of M by the negative radial gradient of diabatic heating rate[2], on the system scale, in association with the rotating convective structures in the presence of surface moisture fluxes from the underlying ocean. This mechanism has been articulated by many authors (e.g., Willoughby 1979, Schubert and Hack 1982). It explains why the vortex expands in size and may be interpreted in terms of axisymmetric balance dynamics (e.g., Bui et al. 2009), wherein the azimuthally-mean force balance in the radial and vertical directions are well approximated by gradient wind and hydrostatic balance, respectively.

2. The second mechanism is associated with radial convergence of M within the boundary layer. It becomes important in the inner-core region of the storm. Although M is not materially conserved in the boundary layer, positive tangential wind tendencies can still be achieved there if the radial inflow is sufficiently large to bring the air parcels to small radii with minimal loss of M. Although the boundary layer flow is coupled to the interior flow via the radial pressure gradient at the boundary layer top, this spin-up pathway is ultimately tied to the dynamics of the boundary layer where the flow is not in gradient wind balance over a substantial radial span. This spin up mechanism cannot be captured by a balance model.

Relationship of tropical-cyclone intensification theory to the SEF problem

Given the widely documented association between SEF and increases in storm size as measured for example by the radius of gale-force (35 knot) winds, a question naturally arises as to if these two spin-up mechanisms might be important also during SEF? The study of Smith et al. (2009) showed that during tropical cyclone intensification there is: 1) a broadening of the outer tangential wind field above and within the boundary layer; and 2) an amplification of radial inflow in the boundary layer in response to an increased radial pressure gradient near its top (associated with the broadening tangential wind field in the outer region of the vortex); and 3) the generation of persistent supergradient tangential winds in the boundary layer just outside of the primary eyewall where the radial wind becomes sufficiently strong.

During this past year the PI has used the new intensification paradigm to propose a new SEF model. The new model underscores the importance of a progressive boundary layer control process that occurs outside of the primary eyewall region. The process involves an unbalanced boundary layer response (second spin up mechanism discussed above) to an expanding swirling wind field (first spin up mechanism discussed above), which ultimately serves to initiate and sustain a ring of deep convective activity in a narrow supergradient-wind zone *significantly outside* the primary eyewall. Recent observational studies on Hurricane Rita (2005) show strong support for the second spin-up mechanism in the concentric eyewall lifecycle. Didlake and Houze (2011) found a supergradient tangential wind at 500-m altitude within Rita's secondary eyewall based on dropsonde data collected during the Hurricane Rainband and Intensity Change Experiment (RAINEX). In complimentary work derived from dropwindsonde analyses, Bell et al. (2012, hereafter BML12) documented that the secondary tangential velocity maximum occurs within the boundary layer of the hurricane Rita, at 600-m altitude.

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[1] The azimuthally-averaged absolute angular momentum ($M = r < v > + fr^2 / 2$) is the sum of the relative angular momentum of the storm's tangential circulation in reference to the surface of the Earth and the planetary angular momentum taken about the storm's rotation axis. Here, r denotes radius from the system center, f denotes the Coriolis parameter and $< v >$ denotes the azimuthally-averaged tangential velocity field defined relative to the system center.

[2] The heating rate refers to the material derivative of the azimuthally-averaged potential temperature, $d < \theta > / dt$, where $< \theta >$ denotes the mean potential temperature and d / dt denotes the material derivative following the azimuthally-averaged secondary circulation.

BML12 found also that the alternating regions of convergence (i.e., the primary and secondary eyewalls) and divergence (i.e., the eye and moat) obtained from dropsondes at 150-m height agree well with the radial distribution of the ascending motion analyzed from the ELDORA Doppler radar data. Taken together, the findings in Didlake and Houze (2011) and BML12 plausibly suggest the operation of the second spin-up mechanism described above for not only the primary eyewall, but also for the secondary eyewall. However, a thorough assessment of each aforementioned spin-up sequence during the early phase of SEF is still needed because of the temporal limitation of observational data during Hurricane Rita. Also, in order to explore the generality of these results other storms need to be studied.

WORK COMPLETED

Our ongoing analysis of TCS08 typhoons Sinlaku (2008) and Jangmi (2008) suggests that the new SEF model is providing new ways of thinking about the SEF phenomenon and can offer new insights into the improvement of numerical weather prediction forecasts and useful forecast guidance to U.S. Naval operations in the Western Pacific sector.

Strong quantitative support for the new SEF model has been presented recently in two peer-reviewed publications by Huang, Montgomery and Wu (2012, hereafter HMW) and Wu, Huang, and Lien (2012, hereafter WHL). Briefly, WHL and HMW used a suite of numerical simulations of Typhoon Sinlaku during the TCS08-TPARC field experiments to analyze the dynamics of SEF. The evidence presented in HMW may be condensed down to three main elements. First, the authors documented a broadening of the tangential winds above the boundary layer associated with spin up mechanism #1 (see their Figs. 1 and 2). Second, the authors documented an intensification of the boundary layer radial inflow over the region of broadening tangential wind (see their Fig. 3). Third, the authors documented the development of persistently increasing supergradient winds within and just above the boundary layer over the region of increasing boundary layer inflow (see their Fig. 5). As described in HMW, the latter two elements are direct consequences of spin up mechanism #2, and further quantitative evidence to support this interpretation is presented below. These three processes were shown in HMW to occur in the region where the secondary eyewall forms. Given the robustness of the results reported in HMW among all 28 ensemble members, the results and dynamical interpretation invite further study and suggest that a scientific breakthrough in this important problem is now at hand.

RESULTS

As part of this year's work, we have made a concentrated effort to further explore the new SEF model and carry out new diagnoses to test the model. As an example of our work in this direction, we have undertaken the question of whether or not the spin up of the tangential winds in the SEF region actually occurs in the boundary layer (mechanism #2). We summarize here the results of a quantitative analysis of the azimuthally-averaged tangential wind tendency using independent numerical simulation data from the published study of Terwey and Montgomery (2008, hereafter TM08), but adopting the new azimuthally-averaged perspective on the intensification dynamics discussed in the foregoing paragraphs. The calculations demonstrate that the origin of the secondary tangential wind maximum, which becomes the secondary eyewall, is the direct result of spin up mechanism #2 and is *not* the result of a downward advection of high tangential winds from above the boundary layer as some have previously speculated. Figure 1 summarizes the evolution of the azimuthally-averaged radial (<u>), tangential (<v>) and vertical (<w>) velocities before the formation of the secondary eyewall in the TM08 simulation using the same timing nomenclature as defined by them (see TM08 for details).

Figure 2 summarizes the tangential wind tendency diagnosis for a period centered around the formation of the secondary eyewall in the TM08 simulation (their hour 23).

In cylindrical coordinates based at the center of circulation, the local time rate of change of azimuthally-averaged tangential velocity can be written as:

$$\frac{\partial\langle v\rangle}{\partial t} = -\langle u\rangle\langle\zeta_a\rangle - \langle w\rangle\frac{\langle v\rangle}{\partial z} - \langle u'\zeta'_a\rangle - \left\langle w'\frac{\partial v'}{\partial z}\right\rangle + \left\langle\frac{1}{\langle\rho\rangle}\frac{\partial p'}{\partial\lambda}\right\rangle + \langle F\rangle \tag{2}$$

Here $\zeta_a = f + \partial(r<v>)/r\partial r$ is the azimuthal mean vertical component of absolute vorticity. The rest of the symbols have either been defined above or represent the eddy counterparts of the mean variables defined hereto. On the right hand side of Eq. (2), the first two terms represent the mean radial flux of mean absolute vorticity and the mean vertical advection of $<v>$; the following two terms represent their eddy counterparts, namely, the eddy radial vorticity flux and the eddy vertical advection of eddy tangential momentum. The fifth term represents the azimuthal perturbation pressure gradient force per unit mass and the last term (*F*) represents the combined effects of surface friction and subgrid-scale diffusion.

Figure 2 displays the terms of Eq. (2) for a calculation centered on hour 23, the time just prior to the emergence of the azimuthally-averaged secondary tangential wind maximum (that occurs within but near the top of the boundary layer in the region of SEF[3], cf. Fig. 1). The term not shown is the azimuthal average of the azimuthal perturbation pressure gradient force per unit mass, which is much smaller than the other terms because the small variation in azimuthal average density. The figure shows the combined contribution of the two mean terms (Fig. 2a), the combined eddy terms (Fig 2b), the local mean tangential velocity tendency (Fig. 2c) and the residual (Fig. 2d). The residual is calculated as the difference between the local time rate of change of mean tangential velocity and the sum of the terms on the right hand side of Eq. 2.

Although Figure 2 displays quantitative information on the various flow contributions to the averaged tangential wind tendency for both the spin down of the primary eyewall and the spin up of the secondary eyewall, we will focus here on the spin up of the secondary eyewall. In particular, we highlight the various contributions to the tendency in the radial region of the SEF, located roughly between about 75 and 150 km radius. In the lowest part of the domain between about 75 and 150 km (Fig. 1f), the mean tangential wind velocity tendency achieves values of about 1 m s^{-1} hr^{-1} (Fig. 2c). This acceleration is the result of the substantially larger and opposing contributions of different terms in the tangential momentum budget. The terms with the largest magnitudes are the combined mean terms (Fig. 2a) and the residual (Fig. 2d). The residual is associated with non-conservative effects due to surface friction, and is maximized in the frictional boundary layer near the surface.

The combined mean terms (Fig. 2a) contribute to a positive maximum tendency mainly below 2 km and between 60 and 120 km radius. By definition, the mean advection terms are the sum of both the

[3]Here and elsewhere we follow Smith et al. (2009) and Smith and Montgomery (2010) and adopt a dynamical definition of the boundary layer, using the term "boundary layer" to describe the relatively shallow layer of strong inflow near the sea surface and which arises largely because of the frictional disruption of gradient wind balance near the surface. It is shown in Figure 1 that for the TM08 simulation analyzed here, the boundary layer so defined is ~1 km deep in the primary eyewall region of the hurricane and somewhat deeper (~1.5 km) in the region of SEF.

radial flux of mean absolute vorticity and the mean vertical advection of $\langle v \rangle$. In the boundary layer, the largest of these two terms is the radial influx of mean absolute vorticity and this influx exceeds 30 m s^{-1} hr^{-1} (not shown). The mean vertical advection of $\langle v \rangle$ attains values of more than -10 m s^{-1} hr^{-1} (not shown) and serves to loft the enhanced tangential wind generated in the boundary layer to the vortex aloft. The mean vertical advection term thus serves as a negative tendency 'sink' in the boundary layer and a positive tendency 'source' in the vortex aloft between 1 and 2 km height.

In the SEF region, the combined effect of the eddy terms to the tangential wind tendency is small overall, negative in the boundary layer and slightly positive above the boundary layer between 70 and 90 km radius (Fig. 2b). Upon examining the individual components of the eddy terms (not shown), we find that the eddy radial flux of eddy absolute vorticity in the region of SEF is largely negative. On the other hand, the vertical eddy advection of eddy tangential momentum accounts for a negative tangential wind tendency below 2 km and a positive tendency above that height. The latter thus contributes to a spin up of the tangential wind above the boundary layer (see Fig. 2b).

The foregoing results demonstrate that even in the presence of a strong spin down tendency associated with surface friction, the actual tangential velocity tendency in the SEF region occurs within but near the top of the boundary layer. The results demonstrate that the dominant contribution to the spin up of the mean tangential wind is associated with the mean radial influx of absolute vorticity in the boundary layer of the vortex. The results indicate moreover that in the region of SEF the main effect of the eddy vertical advection is to redistribute $\langle v \rangle$, serving to spin down $\langle v \rangle$ in the lowest 1 or 2 km and to spin up $\langle v \rangle$ in a layer above that. Together, these findings confirm the operation of the boundary layer spin up mechanism #2 in the region of SEF as foreshadowed above.

IMPACTS

Our ongoing analysis of the Sinlaku (2008) data provides a context for future study of the moist convective dynamics leading to SEF in mature tropical cyclones. Research efforts are continuing with the TCS08 data, the TM08 simulation and other high-resolution numerical simulations capturing the SEF phenomenon.

RELATED PROJECTS

While the TCS08 work on the SEF problem is exclusively supported by ONR, the TCS08 work on tropical cyclogenesis is synergistic with the National Science Foundation experiment called Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) conducted in Atlantic basin during the summer of 2010[4]. A summary of the PREDICT experiment and some first results of the data analysis is given by Montgomery *et al.* (2012) and Smith and Montgomery (2012).

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[4] The P.I. of this ONR grant was also the lead P.I. of the NSF-sponsored PREDICT experiment in 2010.

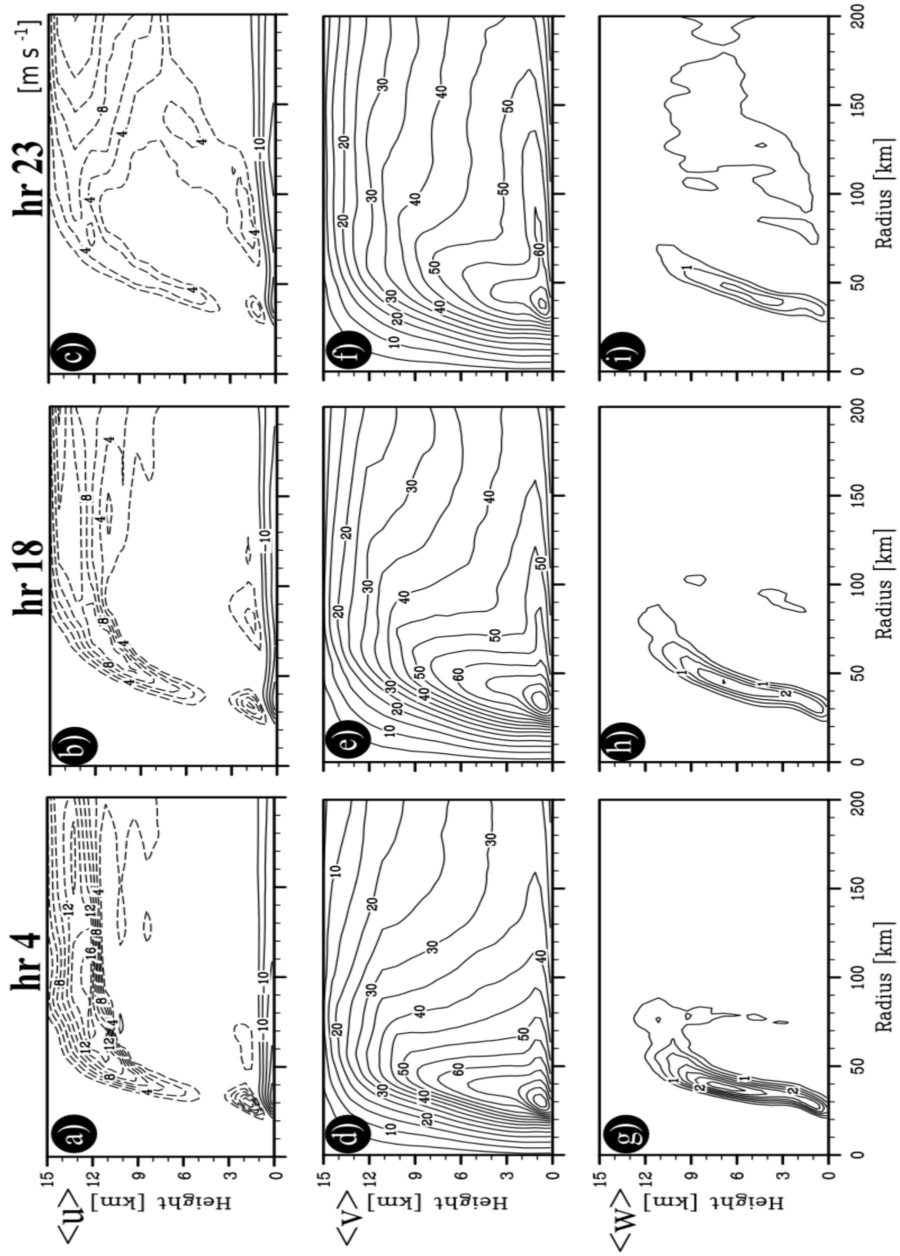

Figure 1. Two-hour and azimuthal average of radial (<u>; top row), azimuthal (<v>; middle row) and vertical (<w>; bottom row) wind components [m s^{-1}], centered at hr 4 (left column), hr 18 (center) and hr 23 (right column) from the mesoscale model simulation of TM08. Contours are plotted every 5 (0.5) m s^{-1}, for the azimuthal and radial (vertical) wind velocities, except for negative contours in the radial wind, which are plotted every 2 m s^{-1}. Dashed lines indicate positive (negative) values in the radial (vertical) wind component. The zero contour is not plotted.

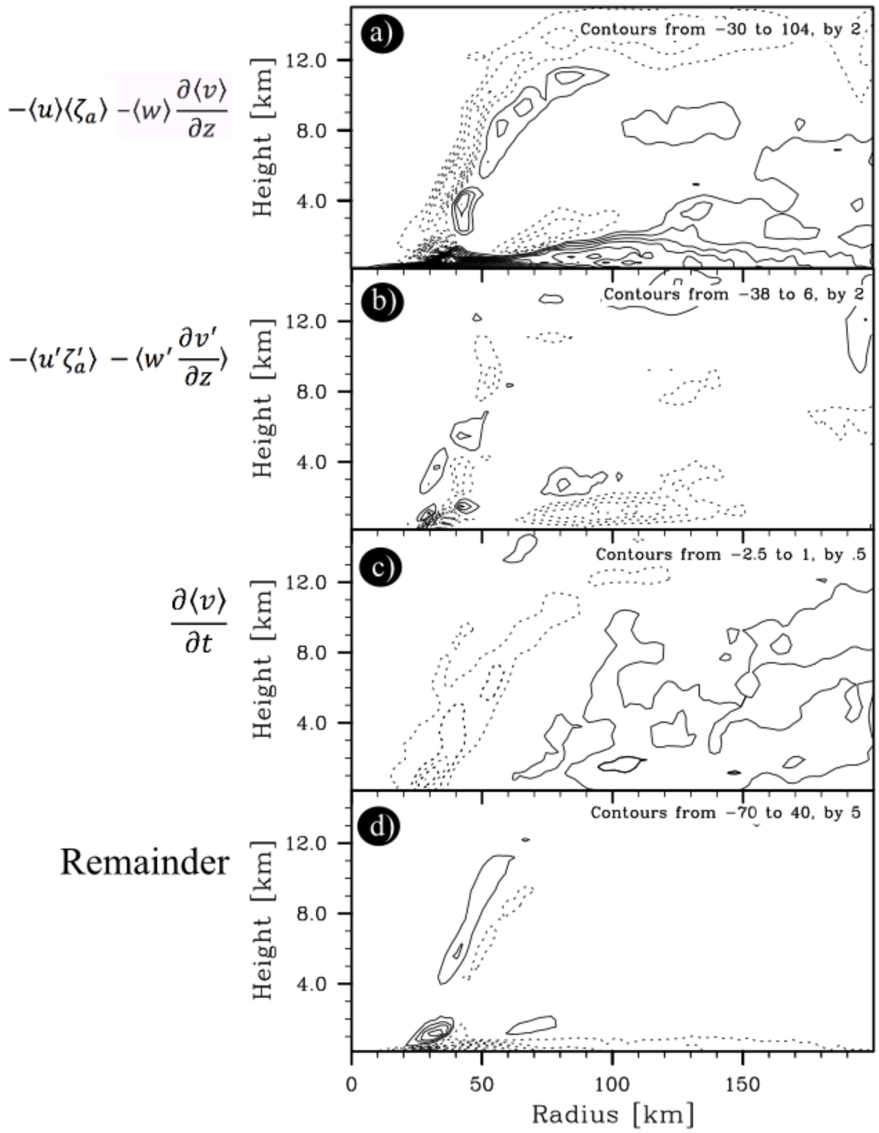

Figure 2. Two-hour average of the terms in the mean tangential velocity tendency equation, centered around hr 23 from the mesoscale simulation of TM08. The terms show are a) the combined contribution of the mean radial vorticity flux and the mean vertical advection of mean tangential momentum, b) the combined contribution of the perturbation radial eddy vorticity flux and the perturbation vertical advection of perturbation tangential momentum, c) the local time rate of change of mean tangential velocity, and d) the mean remainder, estimated as the difference between the third row and the sum of the first two rows. For clarity, contours are shown every 2 m s^{-1} hr^{-1} in panels a) and b), 0.5 m s^{-1} hr^{-1} in panel c) and 5 m s^{-1} hr^{-1} in d), respectively.

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PUBLICATIONS COMPLETED UNDER SUPPORT OF THIS RENEWAL GRANT

[24 total: 21 refereed and published or in press, 2 in review, 1 unpublished]

Bell, Michael M., 2010: Air-Sea Enthalpy and Momentum Exchange at Major Hurricane Wind Speeds. Ph.D. Dissertation. U.S. Naval Postgraduate School, Monterey, CA 93943 [refereed by NPS Ph.D. committee, published as NPS document].

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AWARDS RECEIVED DURING THIS GRANT PERIOD

In September of 2012, the PI was awarded the title of "University Distinguished Professor" from the U.S. Naval Postgraduate School.

In January of 2012, the PI and his co-authors (Drs. Frank Marks, Bob Burpee and Peter Black) were awarded "best scientific paper award for 2010" from the National Oceanic and Atmospheric Administration. The published paper was entitled "**Structure of the Eye and Eyewall of Hurricane Hugo (1989)** and was published in *Mon. Wea. Rev.,* ***136****, 1237-1259*.